METHOD AND APPARATUS FOR GENERATING A
64 STATE 4-D TRELLIS CODE IN DMT

Cross-Reference to Related Applications

The present application claims priority to co-pending United States Provisional Patent Application No. 60/404,390 entitled "Method and Apparatus For Generating A 64-State 4-D Trellis Code In DMT" filed August 20, 2002, the entirety of which is incorporated by reference herein.

Background of the Invention

The present invention relates generally to the field of telecommunications and, more particularly, to data communications over telephone networks and more specifically to voice band modems operating at data signaling rates of up to 33600 bits/second for use on telephone switched networks and leased point-to-point two-wire telephone type circuits in which a method for improving noise immunity using a 64 state four-dimensional (4D) Trellis coder in the DMT (discrete multi-tone) physical layer.

The explosive growth of internet has created a demand for high data rates for home users that rely on standard analog plain old telephone systems (POTS) that use a copper wire twisted pair to carry the information. The need for high-speed access to the home is inevitable due to the availability of information, data, high-bandwidth video and the like from the world wide web and because of such demand, higher speed modems are required; modems operating at higher rates of up to 33,600 bits/second are in use nowadays. A multitude of competing communication technologies provide high-speed

access to the home such as cable modems, digital subscriber line (xDSL) that utilizes the existing analog plain old telephone systems (POTS) that use a copper wire twisted pair to carry the information. Because of bandwidth limitation (4 KHz), and power limitation of the telephone network, line coding schemes are used to encode digital signals into analog signals that convey the analog information over the analog telephone network, such line coding schemes should avoid the undesirable bandwidth or power increase. The line coding schemes manipulate the analog carrier signal which has three attributes, amplitude, phase and frequency of which one or more of such attributes being manipulated by known modulation techniques, one of which is quadrature amplitude modulation (QAM) whereby the carrier signal's phase and amplitude is modulated in order to encode more data within a frequency bandwidth. One example of a QAM modulation system sends two bits of information per QAM symbol, where the digital values can be encoded and the corresponding amplitude and phase can be represented using the constellation. By increasing the constellation size and in the meantime the bit density per symbol will be increased, hence achieving higher data rates. As the constellation size increases, the granularity of the phase and the amplitude difference between different constellation points diminishes, making it increasingly difficult to decode the constellation points, specially in the presence of noise. One way of circumventing such a problem is to increase the Euclidean distance between symbols employing Trellis coding which is a bandwidth efficient, since the symbol rate and, hence the bandwidth is not increased. As the constellation size gets bigger, the problem of detecting constellation due to density increases and shorter Euclidean distance between

symbols, therefore it is desirable to introduce redundancy without doubling the

constellation size. Therefore, a way of counter-acting the effects the short Euclidean

distance between symbols is to partition the quadrature amplitude modulated signal into

subsets, thereby creating an acceptable Euclidean distance between symbols.

Data from a personal computer or other equipment at the customer premise

(CPE) is sent to a transmitter which arranges the data into frame packets; the packetized

signal is then quadrature amplitude modulation encoded and error encoded using trellis

encoding to improve the noise immunity using a convolutional coder to select a sequence

of subsets in a partitioned signal constellation. A numerical symbol vector is trellis

encoded. The trellis encoding starts with the most significant symbol and ends with the

least significant symbol of the vector, a process which employs convolutional encoding

that converts the input symbol to another symbol and then maps the encoded symbol to

its corresponding 16 QAM signal constellation point. The current trellis encoder in the

DMT (discrete multi tone) standard is a 4-D (four-dimensional), 16-state Wei encoder

which is a ¾ encoder with a coding gain of 4.6dB (it varies depending on the bits per

bin). The 4-D symbol is formed by 2 bins, each of which contains 2-D (two-dimensional)

constellations partitioned into four 2-D co-sets which are further partitioned into 8 4-D

co-sets. The minimum squared distance (MSD) of the 4-D co-set is $4d^2_0$ and the branch

minimum squared distance trellis tree is also $4d^2_0$. This invention is an improvement on

the existing 64 state 4-D trellis encoder recommended by the ITU-T (international

telecommunication union).

Since the Euclidean distance between symbols is a paramount feature of the QAM signal, and since the discrete multi-tone modulation scheme employed by some of the high data rate systems such as DSL requires transmitting of at least three DMT symbols per bin, there is a need to use Trellis codes in DMT.

Brief Summary of the Invention

The present invention provides a method and apparatus for encoding data bits in DMT modulation system utilizing a 64-state Trellis encoder in order to achieve further improvement in the achievable coding gain by employing coset partitioning, bit conversion, and constellation encoder that fit the DMT modulation.

In one embodiment of the present invention, a method and system of Trellis encoding is initiated with receiving at least five input data bits and encoding at least four data bits of the received bits using a convolutional encoder , such an encoder employs 4/5 encoding process with at least six stages to encode the bits, the encoded bits are used to generate a redundant bit using a Trellis state machine. The encoded bits, the generated redundant bit as well as any raw uncoded data are passed onto a constellation mapper in order to create two 2-D coset groups, and the state machine is returned to zero once the all the 256 DMT bins are mapped into.

In another embodiment of the a present invention, At the end of each DMT symbol , the Trellis state machine has to be forced to return to 0 state and tied to the state of the state machine as required by the DMT standard. To achieve this, the following constraint has to applied, for both of the final two 4-D symbols, two separate steps are

taken in order to create such state, and to improve rate, the termination may performed

once several DMT symbols or completely eliminated.

Brief Description Of The Drawings

The present invention can be understood more completely by reading the

following Detailed Description of the Preferred Embodiments, in conjunction with the

accompanying drawings and tables.

FIG. 1 is flow chart illustrating the encoding method according to one of the

embodiments of the present invention.

FIG. 2 is an 2-D co-sets of partitioning of the Right constellation.

FIG. 3 is a 2-D and 4-D co-set conversion table.

FIG. 4 is a state machine of a convolution encoder.

FIG. 5 is the conversion mechanism of 2-D co-sets.

FIG. 6 is an state transition table.

FIG. 7 is Co-set transition table.

FIG. 8 is a 3-bit constellation mapping.

FIG. 9 is a table to the top two bits of X and Y in the constellation mapping.

FIG. 10 is a 7 -bit constellation mapping.

FIG. 11 is a simulation of co-set decoding error comparison.

Detailed Description of the Preferred Embodiments

The following description is intended to convey a thorough understanding of the

invention by providing a number of specific embodiments and details involving the

Trellis code in the DMT physical layer for further performance enhancement techniques.

Various improvements and modifications to the preferred embodiments will become apparent to those skilled in the art, and the general principles defined herein may be applied to other embodiments. Therefore, the present invention is not limited to the specific embodiments shown and described, but interpreted to a larger scope consistent with the novel features disclosed herein.

In one embodiment of the present invention and in reference to Figure 1, a method and system of Trellis encoding begins with receiving at least five input data bits in step **110**, and encoding at least four data bits of the received bits using a convolutional encoder in step **115**, such an encoder employs 4/5 encoding process with at least six stages to encode the bits as shown in step **120**, the encoded bits are used to generate a redundant bit using a Trellis state machine in step **125**. In step **130**, the encoded bits, the generated redundant bit as well as any raw uncoded data is passed onto a constellation mapper in order to create two 2-D coset groups in step **135**. In step **140**, the state machine is returned to zero once the all the 256 DMT bins are mapped into, and finally in step **145**, the steps are repeated in order to map the following DMT bins.

In reference to Figure 2, and in accordance to one embodiment of the present invention, a 64-state 4-D Trellis code is employed in the DMT physical layer for further performance enhancement. This Trellis encoder which is based on the 4-D 64-state Wei encoder defined in the ITU-T Recommendation V.34 may cope with the DMT constellation signaling. The theoretical coding gain of the new coder is around 5.63 dB, about 0.96 dB higher than the current Trellis coder in the DMT standard.

According to another embodiment of the present invention, and in reference to Figure 4, a Trellis coder for use in DMT which is an 4/5 systematic coder, and which employs a 6-state finite machine **400**, six-stages **420, 450, 465, 470, 475,** and **485.** The six stage finite state machine **400** receives four bits **405** and generates one redundant bit **495** from the 4 input bits, $u_3 u_2 u_1 u_0$.

The above state machine can be mathematically expressed as follows:

$$X_4 = u_2 \oplus W_2 \oplus W_5$$
$$X_3 = u_1 \oplus W_4 \oplus W_5$$
$$X_2 = u_4 \oplus W_1 \oplus W_3 \oplus W_4 \oplus (u_2 \,\&\, W_5)$$
$$X_1 = u_3 \oplus W_3 \oplus W_4 \oplus (W_5 \,\&\, (W_4 \oplus u_1))$$

In another embodiment of the present invention, and in reference to Figure 5, five input data bits are received **505**, and **510**, where input data bit **505** is passed onto a constellation mapper **525**, while the other four input data bits **510** are encoded in a convolutional encoder **515**, and along with a redundant bit **520**, passed onto the constellation mapper **525**. The encoded bits **510**, the generated redundant bit **520** along with the uncoded bit **505** are mapped into the constellation mapper **525**, and added together using modulo 2 addition generating a first 3-bit group **530** to be inputted into a one DMT bin and a second 3-bit group **535** to be inputted into a one DMT bin. Bit groups **530** and **535** are used to generate a first 2-D coset and a second 2-D coset as shown in the last two columns of Figure 3, and the two 2-D cosets are mapped onto the DMT bins. The overall minimum squared distance (MSD) between the two 2-D cosets is calculated to be $5 d^2{}_0$. And considering the constellation expansion due to adding the redundant bit **520**,

the coding gain is estimated to be around 5.6 dB, slightly varying depending on the total

bits/bin. The resulting state and coset transition diagrams are given in the Figures 6 and 7.

In yet another embodiment of the present invention, to generate create a 3-bit

constellation, each 2-D coset is mapped to one of the 8 points in Figure 8. The number in

the figure represents the 2D coset number ($v'_2 v'_1 v'_0$ or $w'_2 w'_1 w'_0$). And to have the

mapping point to confine within the constellation set compliant with the DMT standard

under the given coset specified by $v'_2 v'_1 v_0$ for bin 1 and $w'_2 w'_1 w'_0$ for bin 2, the

following conversion is needed:

$$v_0 = v'_0$$
$$v_1 = v'_1$$
$$v_2 = v'_3 + v'_2 + v'_1 + v'_0$$
$$v_3 = v'_3$$

where v'_3 is one of the uncoded bits. Together with other uncoded bits, the conversion

bits are fed into the conventional encoder in the DMT standard to obtain X and Y in the

final constellation mapping. Figure 2 is an example of 6 bit constellation resulted from

the above constellation encoder. For bin 2, the same conversion is done on $w'_3 w'_2 w'_1 w'_0$.

In the DMT standard, a table is needed to calculate the last two bits of X and Y to get the

given shape of the constellation for odd-numbered bits constellation. To assign the points

into right cosets with the 64-state Trellis encoder, the table is modified from the DMT

standard, as shown in the Figure 7. Additionally, since the proposed 64 state Trellis is a

4/5 coder, it is difficult to have both 2-D symbols each having a 2 bit constellation. Only

the first 2-D symbol can be set to a 2 bit constellation but assuming $u_5 = 0$ so that the resulting 2-D coset is restricted to 0-3. This can be verified in Figure 3.

In another embodiment of the a present invention, At the end of each DMT symbol , the Trellis state machine of Figure 3 has to be forced to return to 0 state and tied to the state of the state machine as required by the DMT standard. To achieve this, the following constraint has to applied, for both of the final two 4-D symbols of Figure 2, two separate steps are taken in order to create such a state:

$$u_2 = W_2 \oplus W_5$$
$$u_1 = W_4 \oplus W_5$$

and for the last 4-D symbols.

$$u_4 = W_1 \oplus W_2 W_5 \oplus W_3 \oplus W_4 \oplus W_5$$
$$u_3 = W_3 \oplus W_4 \oplus W_5$$

To improve the encoding rate, such termination may be performed once every 256 DMT bins are mapped into.